VOLUME 79 SEPARATE No. D-126

PROCEEDINGS

AMERICAN SOCIETY OF CIVIL ENGINEERS

MARCH, 1953

DISCUSSION OF VARIATION OF WIND VELOCITY AND GUSTS WITH HEIGHT

(Published in April, 1952)

By W. Watters Pagon; Irving A. Singer and Maynard E. Smith; Percy H. Thomas and M. H. Fresen; Robert A. McCormick; Edward Cohen; and R. H. Sherlock

STRUCTURAL DIVISION

Headquarters of the Society
33 W. 39th St.
New York 18, N.Y.

PRICE $0.50 PER COPY

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Technical Division	*Proceedings-Separate Number*
Air Transport	108, 121, 130, 148, 163, 172, 173, 174 (Discussion: D-23, D-43, D-75, D-93, D-101, D-102, D-103, D-108, D-121)
City Planning	151, 152, 154, 164, 167, 171, 172, 174, 177 (Discussion: D-65, D-86, D-93, D-99, D-101, D-105, D-108, D-115, D-117)
Construction	154, 155, 159, 160, 161, 162, 164, 165, 166, 167, 168 (Discussion: D-75, D-92, D-101, D-102, D-109, D-113, D-115, D-121, D-126, D-128)
Engineering Mechanics	142, 143, 144, 145, 157, 158, 160, 161, 162, 169, 177, 179 (Discussion: D-24, D-33, D-34, D-49, D-54, D-61, D-96, D-100, D-122, D-125, D-126, D-127, D-128)
Highway	138, 144, 147, 148, 150, 152, 155, 163, 164, 166, 168 (Discussion: D-103, D-105, D-108, D-109, D-113, D-115, D-117, D-121, D-123, D-128)
Hydraulics	141, 143, 146, 153, 154, 159, 164, 169, 175, 178, 180 (Discussion: D-90, D-91, D-92, D-96, D-102, D-113, D-115, D-122, D-123)
Irrigation and Drainage	148, 153, 154, 156, 159, 160, 161, 162, 164, 169, 175, 178, 180 (Discussion: D-97, D-98, D-99, D-102, D-109, D-117)
Power	120, 129, 130, 133, 134, 135, 139, 141, 142, 143, 146, 148, 153, 154, 159, 160, 161, 162, 164, 169, 175, 178, 180 (Discussion: D-96, D-102, D-109, D-112, D-117)
Sanitary Engineering	55, 56, 87, 91, 96, 106, 111, 118, 130, 133, 134, 135, 139, 141, 149, 153, 166, 167, 175, 176, 180 (Discussion: D-96, D-97, D-99, D-102, D-112, D-117)
Soil Mechanics and Foundations	43, 44, 48, 94, 102, 103, 106, 108, 109, 115, 130, 152, 155, 157, 166, 177 (Discussion: D-86, D-103, D-108, D-109, D-115)
Structural	133, 136, 137, 142, 144, 145, 146, 147, 150, 155, 157, 158, 160, 161, 162, 163, 164, 165, 166, 168, 170, 175, 177, 179 (Discussion: D-51, D-53, D-54, D-59, D-61, D-66, D-72, D-77, D-100, D-101, D-103, D-109, D-121, D-125, D-126, D-127, D-128)
Surveying and Mapping	50, 52, 55, 60, 63, 65, 68, 121, 138, 151, 152, 172, 173 (Discussion: D-60, D-65)
Waterways	120, 123, 130, 135, 148, 154, 159, 165, 166, 167, 169 (Discussion: D-8, D-9, D-19, D-27, D-28, D-56, D-70, D-71, D-78, D-79, D-80, D-112, D-113, D-115, D-123)

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DISCUSSION

W. Watters Pagon,[25] M. ASCE.—A vast number of detailed data on the storm depicted—and on other storms that have been recorded over a period of more than 16 years—have been collected and analyzed by Mr. Sherlock and his associates. The data and the author's analyses are of great value to the engineering profession, and Mr. Sherlock is to be highly complimented on his contribution.

The writer is in accord with the views expressed. The few comments that follow are intended to interpolate a few items of correlative interest and to give a somewhat more geographical breadth to the subject.

The author refers to the writer's use of the 0.157 power for variation with height rather than the 0.143 power (see under the heading, "The Seventh-Power Law"). There is really little choice between these two figures because in the literature on the subject there is a variation from 0.13, as recorded by Scrase[5] for zero temperature gradient, to 0.157, used by Messrs. Prandtl and Tollmien.[5] Also, in 1886, Archibald[5] experimented with anemometers on kites and found a power of 0.192 for instruments at 1,095 ft and 767 ft, and a power of 0.363 for instruments at 250 ft and 102 ft. However, no information was available on the meteorologic conditions prevailing during Mr. Archibald's tests. Nevertheless, the writer finds it interesting that the author derives a combined power of 0.161 when he brings together in Eq. 6 the added effects of height on the uniform velocity and on gusts. This power is close to that of Messrs. Prandtl and Tollmien. Despite the (possible) presence of thermal instability in the storms cited and the entire absence of it in the tests used by Messrs. Prandtl and Tollmien, may it not be possible that the macroscopic flow in the atmosphere and the microscopic flow in pipes follow the same law? If so, a choice of 0.167 is suggested by the writer as a close approximation to fact. This number lends itself to slide-rule computation.

Before utilizing the power law, the author makes an excellent application of the Ekman spirals of 20° and 17° (see under the heading, "Storm Observations"). The writer has made the following rough summarization[26]—the tendency to flow parallel to the isobars is not realized near the earth's surface due to friction. At sea the average angle of deviation is about 10° to 20°, but on land the hills, trees, buildings, and other obstructions may cause an angle as great as 45°. The author's statements concerning the surroundings of his test site, and the fact that he found an angle of from only 17° to 20° indicates that the site was fairly unobstructed. The writer has made some observations on Nantucket Island, which is 30 miles at sea. The southern half of the island is a glacial "outwash" plain and hence an almost perfect

Note.—This paper by R. H. Sherlock was published in April, 1952, as *Proceedings-Separate No. 126*. The numbering of footnotes, equations, illustrations, and tables in this Separate is a continuation of the consecutive numbering used in the original paper.

[25] Cons. Engr., Baltimore, Md.

[5] "Wind Velocity in Relation to Height Above Ground," by W. Watters Pagon, *Engineering News-Record*, Vol. 114, 1935, pp. 742–745.

[26] "Vortices, Eddies and Turbulence as Experienced in Air Movements," by W. Watters Pagon, *Engineering News-Record*, Vol. 114, Part V, 1935, p. 582.

plane surface having a slope of 10 ft per mile or 20 ft per mile. Its surface has no vegetation other than a dense ground cover approximately 6 in. deep and scattered bayberry bushes not more than 4 ft high. On this plain, the writer has observed an angle of approximately 20° or 25° between the surface wind and the wind and clouds aloft during a cool, clear, northeast (hence, offshore) wind at the south shore. In such a summer wind, the sky is clear blue with scattered small clouds. In a warm, humid, but cloudless southwest wind (hence, onshore) the angle is essentially the same. However, in such a wind a "stationary cloud" hovers over the island a little downwind, continually forming upwind, and fragmenting and evaporating downwind. In the first case, the wind comes unobstructed from the Grand Banks, and in the second case, unobstructed from New Jersey; and it is strong even at El. 6 ft. The writer notes[5] that S. P. Wing made tests in Ireland in " * * * open country 65 ft. above sea level and about one-half mile from the ocean behind low rolling sand dunes 70 ft. high * * *." These tests, as well as Mr. Wing's curve, shown in Fig. 3, show a much more rapid increase in velocity with height.

The burden of this discussion thus far is that, although the use of a one-sixth power law fits the author's test data well, it is also quite likely that over large areas of water (and at cities along the oceans, the Gulf of Mexico, and the Great Lakes coasts) a more rapid increase of velocity with height at low elevations is more appropriate, so that the gradient wind is approached more rapidly at low elevations than is indicated by the sixth-power law, thus producing greater pressures on high buildings and bridges.

In the dust squall and the rain squall of a thunderstorm—especially when the storm is a part of an advancing cold front, with the horizontal wind outward from the storm area—the high horizontal velocity usually has a frontal width many times the lateral dimension of all but the very largest buildings and longest bridges. Fig. 9 apparently indicates such an attack. Therefore, it would seem that where such storms are to be anticipated it will be safer not to make the small reduction of from 3% to 8% noted by the author (see under the heading, "Minimum Effective Gusts").

Concerning the vertical distance through which a rapidly falling mass of air passes, it is the writer's recollection that the line squall that caused the destruction of the *USS Shenandoah* raised the ship at approximately 16.4 ft per sec through a height of roughly 3,000 ft, then allowed it to drop again at 25 ft per sec—at which time the altimeter ceased to function—and then raised it again. Such an atmospheric condition is somewhat similar to the breaking of a wave on the foreshore of a beach. The mass of the falling cold air, accompanied by heavy rain, is almost inconceivable, and its kinetic energy is transformed into forward horizontal velocity.

In tropical hurricanes, and typhoons of the Pacific Ocean—such as those which come ashore occasionally—the forces result from the very high horizontal and rotating velocities that are engendered, and that act on a wide front when compared with building dimensions, or even with the length of many bridges. There are no data on the variation with height of the velocity of such storms,

but it would seem reasonable to consider a rapid increase from the effective ground level.

The author properly refers his derived velocities to an "effective ground level." As yet there is no basis, except individual judgment, as to what is the height to assume, other than the 30 ft which the author cites. It would be of great value to the profession were someone to make tests on synthetic cities, composed of model individual houses, or rows of houses, in rectangular array, and of groups of "garden type" or lofty apartment buildings. Probably tests on a water table would give good basis for judgment, the flow about the buildings resembling the flow of water over stones in a rapids, with shooting flow and many eddies and suction effects on the buildings, which simulate rocks.

There are some situations in which, for economic reasons, a structure may be designed for less than the pressure resulting from the maximum recorded wind, and in which damage to person and property cannot occur. For such instances, it is helpful to have some indication as to the probabilities. The writer derived the probabilities of attaining less than absolute maximum velocities over a short period of time in years, and from this tabulated the probability of attaining a gradient wind of the following amounts:[27]

No. of years	Probable 5-min gradient wind velocities, in miles per hour
1	56
2	61
3	65
5	68
8	73
10	76
20	80
50	88
75	91
100	93

These values apply to the Baltimore (Md.) area. From these values, using the power law, the velocity for 5 min at any height can be determined, and then increased to allow for gusts. Following the author's derivation this would be increased for gusts by 50% at El. 30 (see under the heading, "Minimum Effective Gusts").

It is gratifying to have such a substantial basis for the adoption of a gust factor as that presented by the author. Heretofore, the 50% increase has been used purely on the basis of judgment.

In general, the author's treatment of his subject is outstanding.

IRVING A. SINGER[28] AND MAYNARD E. SMITH[29].—An improved approach to the difficult task of deriving design parameters for tall buildings from the wind data that are generally available is embodied in Mr. Sherlock's recent paper on the vertical variation of wind velocity and gusts. The most serious

[27] "Using Aerodynamic Research Results in Civil Engineering Practice," by W. Watters Pagon, *Engineering News-Record*, October 31, 1935, p.601.

[28] Associate Meteorologist, Brookhaven National Lab., Upton, Long Island, N. Y.

[29] Leader, Meteorology Group, Brookhaven National Lab., Upton, Long Island, N. Y.

criticism of the work is that it was based largely on data obtained at only one location (see under the heading, "Storm Observations"), giving rise to the question as to whether it is representative. It is understandable that only a single set of data was used because very few records of the proper type and quality are available, but the basic question of general applicability remains.

In view of this, studies based on data obtained by the Meteorology Group at Brookhaven National Laboratory, Upton, Long Island, N. Y., are compared with the author's results. Such comparisons, although they do not constitute full verification or disproof of the value of the original work, at least provide information from different locations.

Specifically, the study of the extremely violent coastal storm of November 25, 1950, reported by Mr. Lowry,[30] the analysis of one year of hourly wind records by H. A. Panofsky and Mr. Singer,[31] and a recent investigation of wind gustiness by the writers,[32] serve as the basis for the succeeding comments.

A brief description of the installation and terrain is necessary in view of the author's specification (see under the heading, "Summary") of "*** open, level country as a standard of reference ***." Wind measurements were made on a 410-ft meteorological tower, the installation being located near the center of Long Island. The terrain is fairly level and is uniformly covered with scrub oak and pine to a height of from 25 ft to 30 ft above ground.

TABLE 1.—VARIATION OF WIND WITH HEIGHT AT BROOKHAVEN LABORATORY

Height, in ft, above ground	Velocity, in Miles per Hour			Gust Factor[a]	
	Storm average	Fastest 30-min	Fastest 6-min	Observed mean value	Calculated[b] factor, F
37	29.1	33.6	35.1	1.94	1.94
75	37.4	41.2	45.2	1.70	1.86
150	44.7	49.4	53.0	1.60	1.78
410	57.3	61.1	64.2	1.41	1.67

[a] $\frac{V\ (\text{peak})}{V\ (\text{6-min avg})}$. [b] $F = F_{37}\left(\frac{37}{z}\right)^{0.0625}$.

Wind Speed Profiles.—The data for the November 25, 1950, storm were obtained with the instruments operating at normal chart speed, so that it is not possible to specify the exact duration of short-period fluctuations, although their magnitude can be determined. The comparison must therefore be restricted to averages of minutes, rather than seconds. Mr. Sherlock's contention that wind profiles under storm conditions can be described by either logarithmic or power-law approximations seems amply supported (see under the heading, "The Seventh-Power Law"). The Brookhaven data, in which the recorded velocities show even better agreement with theory than those of the author, appear in Table 1.

[30] "The Wind and Temperature Structure of the Lowest 125 Meters During the Storm of November 25, 1950, at Brookhaven National Laboratory," by P. H. Lowry, Internal Report, BNL (unpublished).

[31] "A.E.C. Air Pollution Project, Meteorological Phase," by H. A. Panofsky and I. A. Singer, New York Univ. College of Eng., Technical Information Service, Oak Ridge, Tenn., NYO-1559, June 30, 1951.

[32] "Microclimatology at Brookhaven," by I. A. Singer and M. E. Smith, *Journal of Meteorology* (publication pending).

These results can be fitted by a power-law approximation with a mean error of only 2% for the storm average, but the value of the exponent is 0.274 rather than 0.143 (the one-seventh power law). Thus, for this storm, the one-seventh power law would underestimate the steepness of the wind profile, and a calculation of the 410-ft wind based on 30 miles per hr at 37 ft would be low by 16 miles per hr. The fact that a study of thirteen recent storms indicated a mean value of the exponent of 0.250 shows that these values are typical of the profiles during strong winds in this location.

Gust Factors.—It is unfortunate that the records of the November 25, 1950, storm do not permit a firm comparison of gust factors. The best that can be accomplished is a study of the ratio of the peak speed to the 6-min average speed, without knowledge of the duration of the peaks. It may be anticipated at the outset that the F-values (defined under the heading, "Definitions and Notations") should lie near or above the 0.5-sec and 1.0-sec curves shown in Fig. 6 because the recorded peaks often may have been of very short duration, and the denominator represents a slightly longer averaging period.

The decrease of F with height, and the association of low winds with high gustiness factors and vice versa (see Fig. 5) are both reflected in the Brookhaven data. The mean gustiness factors were as shown in Table 1.

The exponent 0.0625 does not fit the Brookhaven results well. The gust factors decreased more rapidly with height, and a value of 0.147 would have resulted in a much better approximation.

The data for the November 25, 1950, storm also show that the range of speed (peak to lull) changes very little with height, so that the decrease in F is primarily a result of the increase in wind speed (see under the heading, "Gust Factors").

Recommendations.—In summary, it is felt that the author has achieved an approach to the problem that is essentially sound. However, comparison with data from another location casts doubt on the reliability of the values chosen for the parameters, both for wind speed and gust profiles. Brookhaven data indicate that the value of the power in the wind profile equation may be as high as one third. It seems clear that further investigation is necessary in order to determine the most conservative, and, therefore, the safest figures to be used.

The use of standard U. S. Weather Bureau surface observations as a basis for calculation is also an important topic (see under the heading, "Summary"). Mr. Sherlock has specified the necessity of flat terrain and a minimum of obstructions, if adequate data are to be obtained. The importance of this cannot be overemphasized. Each station should be carefully considered before the data are accepted for studies of this type. It is also important to re-emphasize the author's contention (see under the heading, "Gust Factors") that this approach is valid only for high winds (winds greater than or equal to 25 miles per hr at 30 ft). It is not valid at low wind speeds because at low velocities excessive gust factors and different speed profiles occur.

Acknowledgments.—Bendix-Friez Aerovanes were used for the wind measurements at Brookhaven National Laboratory.

PERCY H. THOMAS[33] AND M. H. FRESEN,[34] A.M. ASCE.—The variations of wind velocity and momentary pressures from gusty winds with height are of interest not only to civil and structural engineers but also to the designers of the giant wind turbines proposed for electric utilities.[35,36,37,38] The author's paper and an earlier paper[17] by Messrs. Sherlock and M. B. Stout present material that is almost unique in studies of the intimate nature of the wind and gives an invaluable and indispensable picture of the moment-to-moment behavior of high-velocity winds. The engineer's wind-turbine interest in the paper extends not only to the variation of wind velocity with height above ground, but also to other features that will be mentioned in this discussion.

Wind Velocity Variation with Height.—Table 2 presents some data illustrating the law of the variation of velocity with height that are exceptionally convincing, at least for the first few hundred feet. This table shows, for each month of the year, the average wind velocity at each of the six heights, averaged over the 5-year period from 1945 to 1949. When these data are put in the form of ratios of the velocities at the several heights to the velocity at the 100-ft height, as in Table 2, the ratios are almost identical for each of the months of the year, and their percentage differences from the 5-year averages are small.

TABLE 2.—VARIATION OF AVERAGE WIND VELOCITIES WITH HEIGHT, 1945 TO 1949

Height, in ft above ground	WIND VELOCITY,[a] IN MILES PER HOUR												
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Average
7	4.1 (0.58)[a]	5.2 (0.58)	6.0 (0.61)	6.7 (0.66)	6.7 (0.66)	7.4 (0.67)	6.9 (0.68)	6.1 (0.65)	5.7 (0.63)	5.1 (0.60)	5.0 (0.62)	4.4 (0.58)	5.8 (0.63)
50	5.9 (0.83)	7.4 (0.83)	8.0 (0.82)	8.4 (0.82)	8.7 (0.85)	9.4 (0.85)	8.9 (0.87)	8.2 (0.87)	7.9 (0.87)	7.4 (0.87)	6.9 (0.85)	6.5 (0 86)	7.8 (0.85)
100	7.1 (1.00)	8.9 (1.00)	9.8 (1.00)	10.2 (1.00)	10.2 (1.00)	11.1 (1.00)	10.2 (1.00)	9.4 (1.00)	9.1 (1.00)	8.5 (1.00)	8.1 (1.00)	7.6 (1.00)	9.2 (1.00)
200	8.1 (1.14)	10.2 (1.15)	11.1 (1.13)	11.4 (1.12)	11.6 (1.14)	12.5 (1.13)	11.6 (1.14)	10.6 (1.13)	10.3 (1.13)	9.6 (1.13)	9.4 (1.16)	8.9 (1.17)	10.4 (1.13)
300	8.6 (1.21)	10.9 (1.22)	11.9 (1.21)	12.4 (1.22)	12.5 (1.23)	13.6 (1.23)	12.8 (1.25)	11.9 (1.27)	11.4 (1.25)	10.4 (1.22)	10.2 (1.26)	9.3 (1.22)	11.3 (1.23)
400	9.1 (1.28)	11.3 (1.27)	12.5 (1.28)	13.0 (1.27)	13.1 (1.28)	14.5 (1.31)	13.7 (1.34)	12.5 (1.33)	12.0 (1.32)	11.1 (1.31)	10.6 (1.31)	9.7 (1.28)	11.9 (1.29)

[a] Numbers in parentheses are the ratios of the velocities to those at the 100-ft height.

The exponential equation for the relation of velocity ratios to height ratios can be determined by plotting the logarithms of the ratios on uniform scale cross section paper, or by plotting the ratios themselves on logarithmic paper. The resulting equation for the data in Table 2 was found to be

$$\frac{V}{V_{100}} = \left(\frac{z}{100}\right)^{1/5.4} = \left(\frac{z}{100}\right)^{0.185} \quad \text{(8)}$$

[33] Cons. Eng., Montclair, N. J.; formerly with Federal Power Comm., Washington, D. C.

[34] Engr., Bureau of Reclamation, U. S. Dept. of the Interior, Washington, D. C.

[35] "Power from the Wind," by Palmer C. Putnam, D. Van Nostrand Co., New York, N. Y., 1948.

[36] "Electric Power from the Wind," by Percy H. Thomas, Federal Power Comm., Washington, D. C., March, 1945.

[37] "The Wind Power Aerogenerator," by Percy H. Thomas, Federal Power Comm., Washington, D. C., March, 1946.

[38] "Aerodynamics of the Wind Turbine," by Percy H. Thomas, Federal Power Comm., Washington, D. C., January, 1949.

[17] "Picturing the Structure of the Wind," by R. H. Sherlock and M. B. Stout, *Civil Engineering*, June, 1932, p. 361.

in which V and z designate velocity and height, respectively, and the value of the exponent is 0.185. The logarithmic tangent line from heights of 50 ft through 400 ft is very close to a straight line, the points falling on the line within a very small percentage below 50 ft. The exponent gets smaller for the heights very close to the ground surface, as would be expected. The height of 100 ft was taken as a reference point to avoid the uncertainty of measurements near the ground.

Fig. 3 shows several curves of variation of wind velocity with height, in which a value of $z_o = 30$ ft has been used as a reference height, with a corresponding wind velocity of 50 miles per hr. It can be shown that Eq. 8 can be written in the form:

$$\frac{V}{V_o} = \left(\frac{z}{z_o}\right)^{1/n} \qquad (9a)$$

or more specifically,

$$\frac{V}{V_{30}} = \left(\frac{z}{30}\right)^{1/5.4} \qquad (9b)$$

Table 3 has been computed to compare Eq. 9*b* with Fig. 3, on the basis of a wind velocity of 50 miles per hr at a 30-ft height. The author used the one-seventh power ($1/n = 0.143$) as the exponential relation between velocity and height. The writers determined the exponent as $1/n = 0.185$. Table 3 indicates that Eq. 9*b* at heights of 400 ft and 1,000 ft gives velocities 11% and 16% greater, respectively, than the author's Fig. 3 with $n = 7$.

TABLE 3.—COMPARISON OF WIND VELOCITY EQUATIONS

Height, z, in ft	$\frac{V}{V_{30}}$, from Eq. 9b	VELOCITY, V, IN MILES PER HOUR		Ratio of velocities[a]
		$n = 5.4$	$n = 7$	
(1)	(2)	(3)	(4)	(5)
30	1.000	50.0	50.0	1.00
50	1.099	55.0	53.8	1.02
100	1.250	62.5	59.4	1.05
200	1.421	71.1	65.6	1.08
300	1.531	76.6	69.5	1.10
400	1.614	80.7	72.4	1.11
600	1.741	87.1	76.8	1.13
800	1.836	91.8	80.0	1.15
1,000	1.913	95.7	82.6	1.16

[a] The values in Col. 5 are the values in Col. 3 (from Eqs. 9) divided by the corresponding values in Col. 4 (from Fig. 3).

Mr. Humphreys[39] cites the equation of G. Hellmann:

$$\frac{V}{V_o} = \left(\frac{z}{z_o}\right)^{1/5} \qquad (10)$$

as applicable for heights of from 16 m (52.49 ft) to 300 m (984.25 ft) or 400 m (1,312.33 ft) above the surface, especially over open country. Table 2 and Eq. 9*b* appear to substantiate approximately Mr. Hellmann's value of $n = 5$ in Eq. 10.

[39] "Physics of the Air," by W. J. Humphreys, McGraw-Hill Book Co., Inc., New York, N. Y., 3rd Ed, 1940, p. 140.

Peak Gust Wind Velocities.—Eq. 3 and Eq. 6 indicate that the wind velocities during gusts vary inversely with the 0.0625 power of the height. Table 4 presents a summary of peak gust velocities based on measurements for the same installation as that of Table 2. The selected 9 records in the table, for which ratios are given, are those for peak gusts occurring on the same day at the two heights of 50 ft and 400 ft. These records are believed to be based on nonsimultaneous readings, and are, therefore, not comparable to the author's data in Fig. 12. From this table, it would appear that the nonsimultaneous peak gust velocities vary approximately as the 0.10 power of height based on the average ratio of 1.23 for 9 records.

These few records could not be cited as evidence that wind velocities during gusts vary directly as some exponential power of the height, which would be in contradiction to the author's derivation of Eq. 6, and to his simultaneous velocity readings plotted in Fig. 12. However, Table 4 indicates that, even on days of extremely high wind velocities, the nonsimultaneous peak gust velocities increase as the height increases, within limits not definable from the available data.

TABLE 4.—Ratios of Peak Gust Velocities of Record, for the 7-Year Period, 1945 to 1951

Height, in ft	Peak Velocity, in Miles per Hour												
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year[a]
50	62	56	53	51	71	61	50	50	58	63	64	60	71
400	73	70	66	58	80	84	73	80	66	80	85	74	85
Ratio of the Peak Velocity at 400 Ft to That at 50 Ft													
	1.18	1.25	1.25	1.14	1.13	1.38	...	...	1.14	1.27	1.33	...	1.23[b]

[a] Peak. [b] Average.

Wind Velocity and Gust Considerations Affecting Wind Power.—Because the kinetic energy of the wind varies as the cube of its velocity, height is advantageous to a wind turbine tower. The advantage of height is aided by the fact that the extra cost of high towers is very modest when a design is chosen in which it is possible to increase the base with the height. Such a design is proposed for the 6-legged tower of the Federal Power Commission's 7,500 kw-aerogenerator.[37] A second interesting characteristic of the wind turbine is the fact that only the component of the wind at right angles to the plane of the wheel yields power. When an unevenness of the ground, or an obstacle, causes an upward or a sidewise diversion of the wind stream, there is a corresponding loss of the energy available to a turbine.

There are certain configurations of the ground that contribute something to the available energy of the wind, among which are the summit of a long ridge (or even the sides near the top of a mountain), a wind gap in a hill through which the wind is accelerated, the narrow point in some natural venturi-type ground formation, or the downhill face of a ridge on which the general level is lower on

the lee side of the hill. In the case of the latter the question arises as to whether or not the wind will take an accelerated pace as does the flow of water on the downstream side of a submerged weir. Some observations of Palmer C. Putnam[40] suggest that this may be an important factor. Although the potentialities of these formations are usually accepted, the writers know of no quantitative data available to assist in appraising these potentialities relatively. Any such contribution from civil engineers would be very welcome.

The wheel of the wind turbine must adjust itself automatically to the changes in the velocity of the wind. From the designer's point of view, this fact puts a limit on the danger from gusts in that any gust that takes longer to develop than the time required for the turbine to adjust itself to the changed velocity should be classed as a change in the wind velocity, not as a gust increasing the stresses. The 7,500-kw aerogenerator referred to here adjusts itself to the variations of the wind by changing its speed and overloading the generator on rising winds, which causes a waste of energy by slowing down the wheel. This process is expected to require only a few seconds to be completed, so that only gusts of shorter duration are dangerous.

As the author has pointed out under the heading, "Minimum Effective Gusts," the large blades of these giant turbines would be immune to gusts of short duration and of limited extent. Such gusts would have too little energy to bend the blade enough to reach the safety limit of the material. In large blades, an appreciable time will be so required. However, there is to be considered the extra stress caused by the overrun in a blade continuously exposed to a steady deflecting force. The opportunity and obligation of the builders of a full-sized prototype aerogenerator to resolve such matters is rather intriguing. Suggestions would be in order as to the best methods of measuring the pressure momentarily over the whole surface of a blade 75 ft by 13 ft, front and back (while operating) and for repeating this for a large number of operating conditions. Suggestions would also be in order for conveniently and quickly plotting the local air currents over each of a number of alternative sites, so that the designer of a full-sized wind turbine would have before him a complete picture, covering the various directions, velocities, and types of the prevailing winds.

Although a stationary surface normally exposed to a wind experiences a pressure proportional to the square of the wind velocity, the moving turbine blade is subjected to a unit pressure proportional to the square of the "relative velocity"—a very different matter. The relative wind is the vectorial resultant of the actual wind and the blade speed. Because the blade speed in the turbine mentioned here is thirteen times the wind velocity, the effect is clear. The pressure on the turbine blade is also proportional to the angle of attack of the relative wind against the blade surface, and this angle is nearly proportional to the actual wind speed. As a result, the relative velocity of the wind on the blade does not change with gusts, and the actual stress is increased approximately in proportion to the first power of the gust, as long as the wheel is revolving.

In a number of places in this discussion it has been mentioned that additional information would be helpful in connection with the measurement of wind

[40] "Power from the Wind," by Palmer C. Putnam, D. Van Nostrand Co., New York, N. Y., 1948, pp. 80–81, Fig. 49.

velocities and pressures, and the action of wind in general, as well as that of gusts on moving wind-turbine blades and other structural components of very high aerogenerators. The author has made numerous and extensive investigations in this respect. The engineering profession would be indebted to the author for any comments he would make in this regard in his closing discussion, or to other persons who may pursue the subject further and make known their findings.

Acknowledgment.—Grateful acknowledgment is made to Donald G. Sturges (chief, Operations Division, Hanford Operations Office, United States Atomic Energy Commission (AEC)), for permission to use data (Tables 2 and 4) included herein, and to D. E. Jenne (head, Synoptic Meteorology unit of the General Electric Company), who compiled the data.

Data for Table 2 were taken from the records of wind measurements at six heights at the Hanford Works at Richland, Wash., with the permission of the AEC.

ROBERT A. McCORMICK[41].—An interesting and provocative paper on a subject for which few and limited observational data have been obtained (only a fraction of these data have been published) has been written by Mr. Sherlock. However, analysis of the data recently obtained at Brookhaven National Laboratory (Upton, N. Y.) and by Guggenheim Airship Institute (Akron, Ohio), under P. O. Huff, in cooperation with the U. S. Weather Bureau, should add considerably to the information on the subject.

The validity, for the general case, of any empirical relationship describing the structure of low-level wind in one storm sample, even a "typical" one, must be looked upon with skepticism. Granted that the theoretical relationships are most applicable for average (near neutral) stability conditions—a reasonable assumption for periods of high winds—they contain implied or expressed parameters, such as the roughness length, which must be evaluated locally. In the storm described by Mr. Lowry,[30] the variation of wind speed with height agreed very well with a 1/3.6-power law, but in the storm Mr. Sherlock describes, a fair fit was obtained with the 1/7-power law (see Fig. 2). It is possible to get a slightly better fit for Mr. Sherlock's data using the power law[42] of E. L. Deacon, assuming $\beta = 0.9$. These results are a further indication that the power-law index is quite sensitive to surface roughness under fairly similar stability conditions and serve to discourage the arbitrary application of one set of conditions to another location even when uncomplicated by "unusual" topographies.

More information can be obtained from the expression for the design velocity as a power function of height (Eq. 2), if $\left(\frac{V_z F_z}{V_{30} F_{30}}\right)^2$ from Eq. 6 is

[41] Meteorologist, Weather Bureau, U. S. Dept. of Commerce, Upton, N. Y.

[30] "The Wind and Temperature Structure of the Lowest 125 Meters During the Storm of November 25, 1950, at Brookhaven National Laboratory," by P. H. Lowry, Internal Report, BNL (unpublished).

[42] "Vertical Diffusion in the Atmosphere," by E. L. Deacon, *Quarterly Journal*, Royal Meteorological Soc., Vol. 75, 1949, pp. 89–103.

written

$$\left(\frac{V_z F_z}{V_{30} F_{30}}\right)^2 = \left[\frac{\bar{V}_z \frac{\bar{V}_z + \Delta V_z}{\bar{V}_z}}{\bar{V}_{30} \frac{\bar{V}_{30} + \Delta \bar{V}_{30}}{\bar{V}_{30}}}\right]^2 = \left[\frac{V_z(t)_1}{V_{30}(t)_1}\right]^2 \qquad (11)$$

in which the bars indicate maximum 5-min storm velocities and ΔV indicates the maximum 10-sec (positive) deviations from the $\bar{V}$-value. The expressions $V_z(t)_1$ and $V_{30}(t)_1$ indicate the absolute magnitudes of the 10-sec velocities at heights z and 30 ft, respectively. Thus, the $V(t)_1$-values are the highest observed 10-sec velocities at each level during the time of occurrence of the maximum 5-min velocities, which may not be simultaneous. Therefore, the curve of Eq. 2 should be compared with the variation with height of the $V(t)_1$-values. There is also a possibility that the $V(t)$-values found in 5-min periods with less than maximum mean velocity may exceed the $V(t)_1$ defined in Eq. 11.

EDWARD COHEN,[43] J. M. ASCE.—The French building code regulations for wind—adopted in 1946 by the French Ministry of Reconstruction and City Planning and currently (1952) in use—are based on a variation of velocity with height according to the rule $\left(\frac{H}{10}\right)^{1/7}$, in which 10 is the reference elevation in meters, and H is the height in meters at which the velocity is to be computed. For ease of calculation and to include the effect of gusts, the following formula was given for computing velocity pressures at different levels:

$$\frac{q_h}{q_{10}} = 2.5 \frac{H + 18}{H + 60} \qquad (12)$$

in which q_{10} and q_h are the wind pressures at heights 10 m and H m above the ground, respectively. The limiting ratio $\frac{q_h}{q_{10}} = 2.5$ is reached as H approaches infinity.

The code also specifies a maximum velocity pressure of 162 kg per sq m or approximately 35 lb per sq ft. In effect, this value reduces the difference between the basic and maximum velocity pressures for areas of more severe exposure—as, for example, along the coast line. For structures less than 10 m (32.808 ft) in height, the design may also be reduced according to Eq. 11. For a structure 15 ft high, the loading is approximately 85% of the basic value. Shielding, resonance, shape factor, and other influencing factors are considered separately.

By Eq. 11 the ratio of the pressure at the 1,000-ft level to the basic load at the 33-ft (10-m) level is 2.2, as compared to the value 1.8, the ratio recommended by the author (see Fig. 10). However, in view of the many uncertainties involved and the limited quantity of data available, the agreement appears to be satisfactory.

In writing about gust effect on structures, apparently the author has assumed that the resulting pressures may always be considered static loads. Actually, the computation of stresses resulting from gust pressures is a dy-

[43] Asst. Engr., Ammann & Whitney, Cons. Engrs., New York, N. Y.

namic problem and should be so treated. For example,[44] a gust having an instantaneous time of rise and a duration equal to one half the fundamental period of a simple structure produces an effect equal to that of a static pressure of approximately twice the intensity of the pressure rise. If the duration of the gust is less than one half the fundamental period, the response is reduced as a function of the duration. Thus, at a duration of one tenth of the natural period, the elastic stress in the structure will be approximately six tenths of that caused by a static load of the same intensity. If the gust loading takes longer than two tenths of the natural period to build up to a maximum value, the dynamic effect is also reduced. When the build-up time exceeds approximately four times the natural period, the dynamic effect disappears.

For these reasons, it would be highly desirable to relate gust effects to the dynamic characteristics of the isolated members, frameworks, and buildings subjected to such loading.

R. H. Sherlock,[45] M. ASCE.—In his discussion, Mr. Pagon refers to the fact that many of the older reports on the variation of wind velocity with height fail to include coincidental meteorological data. These data are of great importance. Wind forces acting on structures are significantly large only during strong winds, and these winds occur only during storms when the vertical mixing of the atmosphere is active, with an accompanying high value for the coefficient of eddy viscosity. At the other end of the range of possible meteorological conditions is the temperature inversion, during which the atmosphere is so stable that there is little, if any, vertical mixing, and the coefficient of eddy viscosity is correspondingly small. In the latter case there is little friction between the horizontal layers, and the velocity changes rapidly with height. The pressure gradients accompanying a temperature inversion are never large, and the gradient velocities are, therefore, never great. It is not valid to use the rapid rate of change of velocity with height which occurs in an inversion, when one is considering the matter of variation of storm winds with height. It is interesting, but not surprising, that a wide range of values has been obtained from investigations that were made under possibly various, but unrecorded, meterorological conditions.

Mr. Pagon also raises the question whether, at cities along the ocean and other large bodies of water, a more rapid increase of velocity with height is appropriate than is given by the one-seventh power law. This seems to imply a lowering of the gradient level and to be in accord with the ideas underlying the French Code of 1946, as expressed subsequently in Fig. 14. The table reproduced in Mr. Pagon's discussion indicates that the gradient wind is approached in the coastal zone of Germany at about 750 meters (2,460 ft) which is one half the height at which it occurs in middle Germany (1,500 meters). These great heights represent an average over a long period during which many degrees of stability and instability of the atmosphere may have prevailed. They should not be considered representative of storm conditions without further subdivision and study of the data for stormy parts of these periods.

[44] "Effects of Impact on Simple Structures," by J. N. Frankland, *Proceedings*, Soc. for Experimental Stress Analysis, Vol. VI, No. 2, pp. 9–10.

[45] Prof. of Civ. Eng., Univ. of Michigan, Ann Arbor, Mich.

The same comments apply to the angles of deviation shown in that table. Nevertheless, it is interesting to note that, in fitting curves to the Brookhaven data in Fig. 13, the Ekman spiral required an angle of about 30.5°, and the Rossby spiral required an angle of about 35°. This question is examined later in connection with the discussions by Messrs. Singer and Smith and by Mr. Cohen.

The vertical velocities of the *USS Shenandoah*, cited by Mr. Pagon, are of the same order of magnitude as, although somewhat less than, the rate at which horizontal velocities were propagated downward at the gust fronts examined in the storm quoted by the author. Here again, the coincidental meteorological data would have a bearing on any comparison between these two cases.

The discussion by Messrs. Singer and Smith brings to the structural engineer information which has only recently become available at Brookhaven. It is fortunate indeed that this installation was ready to take records of the storm of November 25, 1950. The criticism has been raised by several writers that this paper has been based largely on data obtained at only one location and for only one storm, thus raising doubts as to whether it is representative of other storms and of locations along coastal areas rather than at inland locations. The data that Messrs. Singer and Smith present are taken from another storm, with wind from the ocean, and from a location near the coast within a network of first-order U. S. Weather Bureau stations. They thus make possible a detailed study of another storm and its coincidental meteorological information.

The data concerning the fastest 6 min of the storm, as shown in Table 1, are plotted in two different ways in Figs. 13 and 14. In Fig. 13, the wind velocity is plotted horizontally, and the height above the ground is plotted vertically. The wind velocities at the four different stations on the tower are shown by small circles. The gradient wind, between 104 miles per hr and 110 miles per hr, and the geostrophic wind, at 138 miles per hr, are shown at the upper right-hand corner of the diagram. In Fig. 13, the letter A designates the curve represented by $V_z = V_{30}\left(\frac{Z}{30}\right)^{0.25}$, the letter B designates the Ekman spiral, and the letter C designates the Rossby spiral.

The information for computing the gradient and geostrophic winds was taken from a report prepared under the direction of Ernest J. Christie.[46] In this report, synoptic maps are shown for the period from November 24, 1950, to November 27, 1950, at intervals of 6 hr. The pressure gradient in the region of Long Island appeared to be greatest on the map for the hour of 1330 Eastern Standard Time (1830 Greenwich Standard Time) on November 25, 1950. At this time the center of the storm was in southeastern Pennsylvania and was moving approximately north. The arrows show that the wind was coming from the east at Brookhaven. This is supported by the tabulations, which also show that this hour was within the period of strongest winds as given by the hourly velocities at the 37-ft level. It was assumed that the

[46] "Report on the Storm of November 25, 1950," U. S. Weather Bureau Office, New York, N. Y., December, 1950.

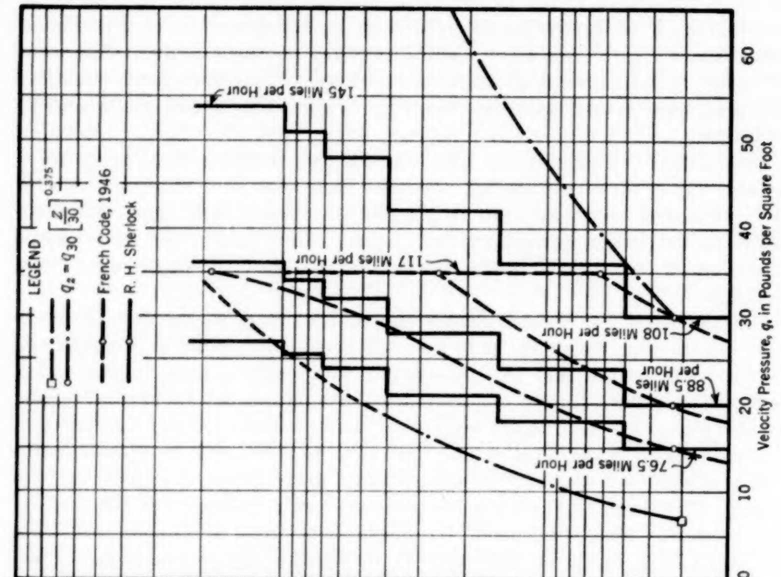
LEGEND
$q_z = q_{30}\left[\frac{z}{30}\right]^{0.375}$
French Code, 1946
R. H. Sherlock
145 Miles per Hour
117 Miles per Hour
108 Miles per Hour
88.5 Miles per Hour
76.5 Miles per Hour
10
20
30
40
50
60
Velocity Pressure, q, in Pounds per Square Foot

FIG. 14

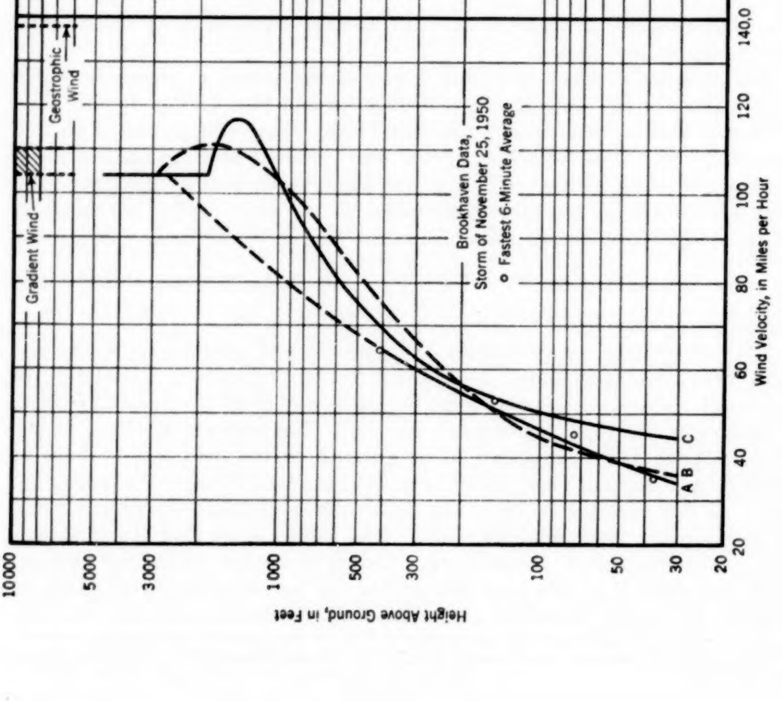
Gradient Wind
Geostrophic Wind
Brookhaven Data, Storm of November 25, 1950
o Fastest 6-Minute Average
A
B
C
20
40
60
80
100
120
140,0
Wind Velocity, in Miles per Hour
10000
5000
3000
1000
500
300
100
50
30
20
Height Above Ground, in Feet

FIG. 13

pressure gradient obtained from this map was related to the fastest 6-min velocities of Table 1.

The gradient as scaled from the map was 24 millibars in 210 miles. This is equivalent to 7.1 millibars per 100 kilometers. The radius of curvature of the wind path in this area varied from 1,450 kilometers (900 miles) to 1,880 kilometers (1,170 miles), depending whether the wind direction arrows or the isobars were used as a basis of measurement. The gradient velocity based on this information and computed by standard methods for a latitude of 41°, varied from 104 miles per hr to 110 miles per hr, and the geostrophic wind was equal to 138 miles per hr. The gradient wind velocity of 104 miles per hr is considered the most reliable estimate, and this value has been used in fitting these curves.

Of the three curves used, one is an empirical exponential curve with the value of the exponent taken at 0.250. This value is referred to by Messrs. Singer and Smith as being the mean value obtained from a study of thirteen recent storms at Brookhaven. The other two curves are spirals. The one by Mr. Ekman, previously described, is based on a theory of eddy viscosity, and the other one by Mr. Rossby is based on the theory of the "mischungsweg" (mixing length).[47] The curves have been spread somewhat for the sake of clarity and, therefore, they are not exactly the best fit. For example, the Rossby curve (curve C) could be made to pass among the three upper points by changing from a velocity of 45 miles per hr at a height of 30 ft to a velocity of 42 miles per hr. However, the curves illustrate the relation between the actual observations of wind velocity and the two theories. In this case, a Rossby spiral fits the data better than does the Ekman spiral, although the difference is not great.

The two spirals reach the 1,000-ft level at approximately the same value for the wind velocity, namely, 104 miles per hr. The exponential curve, if extrapolated beyond the level of 410 ft, reaches the 1,000-ft level at a wind velocity of only approximately 82 miles per hr. Shall the velocities at higher levels be obtained by a simple extrapolation of the nontheoretical (empirical) curve, or shall the curves that represent a theoretical approach be used for purposes of extrapolation? In this connection it should be noted that the fastest 6 min, as recorded by Messrs. Singer and Smith in Table 1, did not occur simultaneously at the 4 stations on the tower, and that the individual 6-min intervals were separated by as much as 2.5 hr.

In Fig. 14, the French recommendations, as reported by Mr. Cohen in his discussion, have been superimposed upon the recommendations of this paper for further comparison. Fortunately, the effective ground level is taken at approximately the same height in both cases, being 30 ft for this paper and 10 meters (32.8 ft) in the French Code. This makes comparison relatively easy. Two curves adapted from the Brookhaven data are shown also.

It will be seen that, if the basic velocity pressure is taken at 15 lb per sq ft, the recommendations of the French Code exceed those of the writer for all heights from 10 meters to 2,000 ft, except between 50 ft and 65 ft. At

[47] "A Generalization of the Theory of the Mixing Length with Applications to Atmospheric and Oceanic Turbulence," by C. G. Rossby, *Metorological Papers*, Vol. I, No. 4, Massachusetts Inst. of Technology, Cambridge, Mass., 1932, p. 33.

1,000 ft, the French Code recommends a velocity pressure of 33 lb per sq ft, but the writer has recommended 27 lb per sq ft. For those geographical areas in which a basic velocity pressure of 15 lb per sq ft is justifiable, the French Code is more conservative, but in those areas where a basic velocity pressure of 30 lb per sq ft is justifiable, the two recommendations are substantially the same to a height of 150 ft, above which this paper is much more conservative.

The use, by the French Code, of a constant velocity pressure of 35 lb per sq ft above the height of 62 ft is probably based on two assumptions. The first of these assumptions is that, within the geographical areas served by that code, the same gradient velocity is equally probable at all locations, and that the difference between the gradient velocity and that which is experienced at the effective ground level is almost entirely due to eddy viscosity caused by the roughness of the terrain over which the wind is blowing, and only to a minor extent by the thermal mixing. The second assumption is that, at the exposed coastal areas where a basic velocity pressure of 30 lb per sq ft would be justifiable, the gradient velocity would be found at a height of 62 ft above the ground, and that at some inland location, where records call for a velocity pressure of only 15 lb per sq ft, the gradient velocity would not be found below a height of 1,850 ft.

In Fig. 14, two curves adapted from the Brookhaven data are also shown, using the form of Eq. 6. For example,

$$q_z = q_{30}\left[\left(\frac{Z}{30}\right)^{0.250}\left(\frac{Z}{30}\right)^{-0.0625}\right]^2 = q_{30}\left(\frac{Z}{30}\right)^{0.375}.$$

The exponent 0.250 for the variation of wind velocity with height (6-min average), is based on the Brookhaven data, but the exponent -0.0625 has been retained from the writer's recommendation for the variation of gust factors with height even though it seems too conservative on the basis of the observations at Brookhaven. This exponent is on the safe side. Furthermore, it makes allowance for those cases in which the strongest gust does not occur in the 5-min period having the highest average velocity. This point is discussed in connection with Figs. 5, 6, and 7. It also makes allowance for atmospheric jets. The 6-min velocity of 35.1 lb per sq ft at an elevation of 30 ft was multiplied by a gust factor of 1.5. This was reduced to velocity pressure by the expression, $q = 0.00255\ [35.1 \times 1.5]^2$, and the curve was drawn on the basis of the foregoing equation. The curve, if extrapolated, would reach the velocity pressure of 35 lb per sq ft at about the same elevation as the French Code, even though it started at an elevation of 30 ft with only half the pressure of the French Code. Also, when a basic velocity pressure of 30 lb per sq ft is assumed at 10 meters, the application of the equation based on the Brookhaven data yields a velocity pressure of 65 lb per sq ft at a height of only 240 ft. If extrapolated to a height of 1,000 ft, it would yield a velocity pressure of 111.5 lb per sq ft. These values are entirely out of agreement with any existing practices and seem much too conservative. It seems that the curve based on the Brookhaven data is, while more conservative, not far out of agreement with the recommendations of this paper when applied to the variation of wind velocity with height accompanying fairly low basic velocities at 30 ft. How-

ever, when the same equation is applied to the higher velocity pressures, such as 30 lb per sq ft, which are justified in exposed coastal areas subject to the hurricane type of storm, the curve yields velocity pressures that are far too conservative.

When dealing with the higher ranges of velocity pressures, it seems that the truth must lie somewhere between the very optimistic requirements of the French Code and the extremely pessimistic predictions based upon the Brookhaven data. It may well be that the writer's recommendations, which lie between the French requirements and the predictions based on the Brookhaven data, are not the best that could be obtained for exposed coastal areas subject to hurricanes. However, the writer is not familar with any storm observations that would justify the assumption that the gradient velocity may be found at an elevation of only 62 ft above the ground anywhere in the United States. Of course, during periods of deep temperature in versions, the gradient velocity might very well be found at low elevations—but this would involve little or no vertical mixing and would occur when the wind velocity was so small that it would have no significance in the design of structures. Furthermore, eddy viscosity, which has such an important part in fixing the height of the gradient level, is not caused entirely by ground roughness but is caused likewise by thermal instability of the air and this may also occur over large bodies of water. Thus, it seems better to assume that, during periods of strong storms when vertical mixing in the atmosphere is extremely active, there is no lowering of the height at which the gradient velocity is reached. No justification is evident for the adoption of a constant velocity pressure of 35 lb per sq ft above 62 ft anywhere in the United States, especially considering the uncertainties that exist in regard to the variation of velocity with height under hurricane conditions. On the other hand, the adoption of a purely empirical curve based on the Brookhaven data, as a guide in choosing a variation of velocity with height, would lead to results implying that gusts exist having a velocity of 158 miles per hr at 240 ft, and of 210 miles per hr at 1,000 ft. These values would be true velocities reduced to standard atmosphere at sea level, not velocities from the old 4-cup anemometers that "overshot" the true velocities by about 40%.

Messrs. Thomas and Fresen introduce a subject that at first sight may seem unrelated to the work of structural engineers—namely, the subject of power from the wind. However, a little consideration convinces one that the wind loading of structures incident to the support of such generating stations cannot be dismissed as being trivial. This part of their discussion will undoubtedly prove a worthwhile contribution in this unusual field.

The velocities listed by Messrs. Thomas and Fresen in Table 2 are the averages over a considerable period of time. No doubt, they include velocities occurring during every conceivable degree of stability and instability, and these would include the very rapid increase of velocity with height during periods of temperature inversions. Therefore, it is questionable whether or not the exponent 0.185, which they obtained, should be used for storm periods in that area without separating the data on that basis. The tendency would be for their data to show a higher exponential value than the data taken during

storm periods. Nevertheless, their data constitute a contribution and will undoubtedly be taken into consideration by the ASCE Structural Division Committee on Wind Forces.

The exponent -0.0625, which was used by the writer in Eq. 6 to describe the variation of gust factors with height, cannot be compared with the ratio of peak gust velocities at two different heights. This is because the gust factors must necessarily be used with some average velocity, either coincidental or adjusted so as to be applicable in the use of the Weather Bureau records for the daily fastest 5-min velocity. This point is explained in connection with Figs. 6 and 7. For example,

$$\frac{\text{Peak velocity at } Z}{\text{Peak velocity at 30}} = \frac{V_z F_z}{V_{30} F_{30}} \neq \frac{F_z}{F_{30}}.$$

Messrs. Thomas and Fresen present an interesting but different scheme for describing gusts.

Mr. McCormick describes a method for taking care of those cases in which the highest peak velocity occurs within a 5-min interval that does not have the highest average velocity of the storm sample, thus making possible the use of the Weather Bureau records of the daily fastest 5-min velocity. His point is an important one, as described and provided for in connection with Figs. 6 and 7.

Mr. McCormick's pessimism regarding the transfer of empirical information from one location to another is understandable, but this should not be taken as a prohibition against the attempt to find improved engineering solutions for difficult problems. For several generations, engineers have been designing and constructing wind-loaded structures on the basis of even more meager empirical information than now exists. One of the novel features of the data presented in this paper and of the data from Brookhaven is that in each case it has been possible to supplement the empirical information from the towers with theoretical interpretations based on coincidental observations of pressure gradients. It is hoped that the meteorological towers at Brookhaven and at Hanford, Wash., will provide additional storm information supplementing the rather limited empirical data available to the engineer. It is further hoped that these installations may some day be equipped with more sensitive anemometers that will yield more refined information as to wind structure. Because of the high cost of such installations, perhaps it is too much to hope that additional installations such as this will be built in other parts of the country and thus provide data for other locations and types of storms.

It is gratifying to note that Mr. Cohen is drawing attention to the dynamic response of gust-loaded structures. It was not the intention of the writer to imply that this dynamic response might be ignored. It is generally recognized that the dynamic response of a structure to a gust will sometimes involve stresses considerably in excess of those that would exist if the stresses had been computed on the basis of static loads. Perhaps one reason for the increased interest in this matter is the recent necessity for investigating the

effects of bomb blasts. Another reason may be the more frequent use of tall flexible towers and steel chimneys.

The mechanics of computing a structure's elastic response to fluctuating or suddenly applied loads have been well established and accepted by engineers. However, there is an aerodynamic time-lag between the passage of a gust front and the response of the structure, and this fact has not been generally recognized by structural engineers. This time-lag is not dependent upon the elastic properties of the structure but upon its aerodynamic properties. It is obvious that, aerodynamically, a structure will not be fully affected by a gust that is only a small fraction of the size of the structure. A gust must have sufficient vertical and horizontal extent to envelop not only the structure but also those flow patterns to the windward and to the leeward that are responsible for the maximum pressures upon the structure. This matter is discussed under the heading, "Minimum Effective Gusts" and in other publications.[22,23,24] Relative to Mr. Cohen's mention of "* * * a gust having an instantaneous time of rise and a duration equal to one-half the fundamental period of a simple structure * * *," it must be explained that there is no such thing as an instantaneous gust when one speaks of the applied forces on the structure. The gust must have a length of several times the size of the structure before the pressures incident to that gust have been completely established on all sides of the structure. Unfortunately, this aerodynamic time-lag has not been experimentally evaluated for sharp-edged bodies. The only experiments known to the writer are those performed by W. S. Farren on airfoils, as discussed under the heading, "Minimum Effective Gusts," and referred to elsewhere.[22] The evaluation of the aerodynamic time-lag on sharp-edged structures awaits further experimental evidence. Such experiments are now being undertaken at the University of Michigan in Ann Arbor.

The question raised by Mr. Cohen deserves further consideration in a separate paper devoted to that subject. However, a complete treatment of this subject would require (*a*) that the gust be separated from the average velocity upon which it is superimposed, (*b*) that the aerodynamic time-lag for that particular type of structure be known, (*c*) that a minimum effective gust be properly chosen, and (*d*) that the elastic response of the structure be computed.

Summary of Closing Remarks.—In closing, the writer wishes to express his thanks to those who have participated in the discussion of this paper. He feels that the future work of the ASCE Committee on Wind Forces Acting on Structures has been more clearly indicated in so far as the variation of velocity with height is concerned.

Some of the items in the writer's "Summary" are in need of modification. Item 8 should read: The one-seventh power law is a sufficiently close approximation to the variation of wind velocity with a height up to 1,000 ft, above which a constant velocity is justified. An exception should be made in coastal

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[22] "Gust Factors for the Design of Buildings," by R. H. Sherlock, *International Assn. for Bridge and Structural Eng. Publications*, Zurich, Switzerland, Vol. 8, 1947, pp. 221–222.

[23] *Proceedings*, 3rd International Cong. for Applied Mechanics, Stockholm, Sweden, 1930, p. 329, Fig. 8.

[24] "Gust Factors for the Design of Buildings," by R. H. Sherlock, *International Assn. for Bridge and Structural Eng. Publications*, Zurich, Switzerland, Vol. 8, 1947, p. 220.

areas exposed to hurricane conditions and in other areas in which the records justify a basic velocity pressure above 20 lb per sq ft. Recommendations for such areas should await further study by the ASCE Structural Division Committee on Wind Forces. Item 9 should read: The variation of gust factors with height is adequately represented by Eq. 3, except for the areas mentioned in Item 8. Item 10 should read: The combined effect of the variation of maximum wind velocity with height and of maximum gust factors with height is given by Eq. 6, except for the areas mentioned in Item 8.

Corrections for Transactions.—In *Proceedings-Separate No. 26*, Page 2, line 13, in place of ". . . the Interior," read ". . . Commerce." Page 20, line 5, in place of ". . . in open, country," read ". . . in open country." Fig. 10, in place of "Eq. (3)," read "Eq. (6)."

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